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ORIGINAL ARTICLE

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Perceived indoor air quality in naturally ventilated primary schools in the UK: Impact of environmental variables and thermal sensation

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Abstract

Indoor air quality (IAQ) in classrooms has a significant impact on children's academic performance, health, and well-being; therefore, understanding children's perception of IAQ is vital. This study investigates how children's perception of IAQ is affected by environmental variables and thermal sensation. In total, 29 naturally ventilated classrooms in eight UK primary schools were selected and 805 children were surveyed during non-heating and heating seasons. Results show that air sensation votes (ASVs) are more correlated to CO₂ levels than to operative temperatures (T_{op}) during non-heating seasons and more correlated to T_{op} than CO₂ levels during heating seasons. The impact of T_{op} on ASVs decreases with an increase in CO₂ levels, and the effect of CO₂ levels on ASVs decreases with increase in T_{op}. The most favorable ASVs are given when children feel "cool" and have "as it is" preference. By keeping CO₂ < 1000 ppm and T_{op} within children's thermal comfort band, ASVs are improved by 43%. The study recommends that standards should consider the impact of both temperature and CO₂ levels on perceived IAQ. Perception of IAQ also affects children's overall comfort and tiredness levels; however, this influence is more significant on tiredness level than that on overall comfort level.

KEYWORDS

air sensation votes, children's perception, CO₂ levels, indoor air quality, naturally ventilated, operative temperature

1 | INTRODUCTION

Classrooms are the second most important indoor environment for children after their homes¹ because children spend around 25%–30% of their life in schools.^{2–4} Concerns over adverse effects of poor indoor air quality (IAQ) on children's health, productivity, and well-being are growing,^{5–8} especially because indoor air can be 10 times as polluted as the outdoor air in real conditions.⁹ Poor IAQ leads to some psychological or physiological costs,¹⁰ and influences students'

health and performance, especially in younger ages.¹¹ Building regulatory frameworks for the provision of adequate IAQ is framed around CO₂ levels rather than other pollutants.¹² IAQ is often characterized by CO₂ concentrations,^{13–18} in buildings where exhaled air, people, or bio-effluents are the main pollution sources.^{19–21} Carbon dioxide (CO₂) as the most important human bio-effluent^{22–24} is produced by human respiration¹⁴ in proportion to their metabolic rate.²³

The introduction signifies the importance of CO₂ levels on children's absenteeism, health, and academic performance by reviewing

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the results of several studies. Studies have shown that children's exposure to poor IAQ increases school absenteeism²⁵ and deteriorates respiratory system.²⁵⁻²⁷ The study by Shendell et al (2004) shows that when CO₂ concentrations increase by 1000 ppm, around 10%-20% of absenteeism is increased.¹³ Seppänen et al (1999) suggest that decreasing CO₂ concentrations below 800 ppm can decrease the risk of sick building syndrome (SBS) symptoms, such as headache, fatigue, or eye/throat irritation.²⁸ Myhrvold et al (1996) show that CO₂ concentrations greater than 1500 ppm may lead to headache, dizziness, tiredness, difficulties in concentrating, and unpleasant odor in classrooms.²⁹

It is shown that adverse health effects and absenteeism caused by poor IAQ can negatively affect children's academic performance.^{30,31} Several studies have found a negative correlation between high CO₂ levels and performance on cognitive and concentration tests.³²⁻³⁴ Coley et. al (2007) show that increase of CO₂ levels from a mean of 690 ppm to a mean of 2909 ppm leads to a 5% decrease in Power of Attention.³² Berner (1993) shows that average students' test scores increase 5.4 points ($P < .05$) for each improved category of building conditions (ie, "poor" to "fair" to "excellent").³⁴ Myhrvold et al (1996) by studying 550 subjects aged 15-20 in 20 classrooms in Norwegian schools show that increased CO₂ levels, corresponding to 0-999, 1000-1499, and 1500-4000 ppm, are associated with mean performance indices of -0.8, 0.02, and 0.13, respectively (negative scores representing better scores).²⁹ Children as the main occupants of primary schools represent a vulnerable group³⁵⁻³⁸; therefore, improving IAQ is significant for them. Above-mentioned studies highlight the impact of CO₂ levels on IAQ, health, and productivity; however, children's perception of IAQ with regard to environmental and sensation variables is less investigated, especially in primary schools.

It is important to investigate school children's perception of IAQ due to their physical and physiological differences with adults. Physically, young children are more susceptible to indoor air pollution compared to adults due to higher air intake in proportion to their body weight³⁹⁻⁴³ and less developed organs, tissues, and immune system.⁴² Physiologically, children have higher respiration and metabolic rates.⁴⁴ External factors such as type of work^{30,45} and stress level⁴⁶ can also impact children's perception of IAQ negatively. Since primary school children's perception of IAQ is less investigated, the study aims to investigate the association between children's perception of IAQ with environmental variables (such as CO₂ levels and operative temperature) and thermal sensations in naturally ventilated classrooms. It also looks at the impact of children's air sensation votes (ASVs) on their overall comfort and tiredness levels.

2 | METHODOLOGY

The five main steps carried out in this methodology are as follows: (1) defining research design; (2) sampling climate, buildings, and occupants; (3) acquiring data on children's perception of the indoor environment and environmental measurements; (4) evaluating

Practical Implications

- Air sensation votes are correlated with the last 5 minutes of CO₂ measurements.
- Perception of air quality is affected by CO₂ levels and operative temperature.
- When children feel "hot or cold," air sensation votes are the least favourable.
- When "CO₂ < 1000 ppm and T_{op} < 23°C," perception of air quality is improved by 43%.
- Standards should consider the impact of both operative temperature and CO₂ levels on perceived IAQ.
- Better perception of indoor air quality results in higher overall comfort votes.

classrooms' IAQ against standards; and (5) reviewing statistic methods for analysis.

2.1 | Research design

The design of the study defines transverse sampling in which according to Nicol et al (2012) bias is lowered or avoided; thus, the results are more representative.⁴⁷ The problem with longitudinal sampling in this type of study is that many intervening variables may affect studied variables during a lengthy time.⁴⁸ There is a danger of sampling bias in longitudinal studies⁴⁷ which is due to the small population. Participants might lose interest in participating due to high frequency of surveys⁴⁹ in longitudinal studies. Hence, data acquisition and observations were carried out in 29 different classrooms on 29 distinct days throughout one year. To increase the validity of the study and reduce bias, the number of studied classrooms is similar during both seasons, 15 classrooms during non-heating and 14 classrooms during heating seasons.

2.2 | Sample selection

Samples were selected with specific attention to climate, buildings, and observed occupants.

2.2.1 | Location

Schools were selected in the *mild* climate of UK for two main reasons: (1) Mild or temperate climates where the outside temperature is lower than indoor temperature can provide opportunities for buildings' natural ventilation, as supported in several other studies.⁵⁰⁻⁵² Mumovic, et al. (2018) suggest that outdoor temperature in the UK is lower than the indoor temperature for most of the year during both day and night⁵¹; therefore, window opening can ventilate and cool

TABLE 1 Classroom's architectural features and configurations

Mode/Date	General		Classroom		Window Design			Ventilation	MHW ⁵	W Operation	Exterior Door	
	No.	Floor	Orn ¹	Area	Vo ²	WA ³	NW ⁴					W Type
Non-heating July and Sep 2017	1.1	First	NE	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre opening	1	Manually	No
	1.2	First	SW	60		8	8			1	Manually	No
	1.3	First	SW	60		8	8			1	Manually	No
	1.4	First	SW	60		8	8			1	Manually	No
	2.6	First	NW	60	192	8	8	Top-hung outward openings at 2 levels	Single-sided windows at 2 level + louvre openings	1	Manually	No
	2.7	First	SE	60		8	8			1	Manually	No
	2.8	First	SE	60		8	8			1	Manually	No
	2.9	First	NW	60		8	8			1	Manually	No
	Heating Oct & Nov 2017 Jan and Feb 2018	3.10	Ground	S &W	65	227	2	5	Top-hung outward	Single-sided	1.7	Manually
3.11		Ground	S &W	70	245	2.2	6		Double-sided	1.6	Manually	No
3.12		First	NW	60	192	2.5	5		Single-sided	2.6	With handle	No
4.13		Ground	W	50	130	0.5	2	Top-hung outward	Single-sided	1.8	Manually	Yes
4.14		Ground	W	60	156	0.5	2			1.8	Manually	Yes
4.15		Ground	No W	50	175	0	0	-	No opening	-	No window	No
5.16		First	SW, SE	55	137	5.7	8	Top-hung openings at 2 levels	Single-sided at two levels	0.5	Manually	No
5.18		First	SW & NW	55		5.7	8			0.5	Manually	No
5.20		Ground	SW & NW	55		5.7	8			0.5	Manually	Yes
6.21		First	SE	60	168	1.8	4	Top-hung outward opening	Single-sided windows + Louvre openings	2.3	Remote-control	No
6.22		First	SE	60		1.8	4			2.3		No
6.23		First	SE	60		1.8	4			2.3		No
6.24		First	SE	60		1.8	4			2.3		No
6.25		First	SE	60		1.8	4			2.3		No

(Continues)

TABLE 1 (Continued)

Mode/Date	General		Classroom			Window Design			Ventilation	MHW ⁵	W Operation	Exterior Door
	No.	Floor	Orn ¹	Area	Vo ²	WA ³	NW ⁴	W Type				
Non-heating April and May 2018	7.26	Ground	SE & SW	70	252	3.9	6	Top-hung outward opening	Double-sided	2.7	With handle	No
	7.27	Ground	SE & SW	55	137	3.3	3		Single-sided	1.65	Manually	Yes
	7.28	First	NE & NW	55	137	5.4	6		Double-sided	1.6	Manually	No
	8.29	Ground	NE	60	150	2.2	4	Top-hung outward opening	Single-sided	1.4	Manually	Yes
	8.30	Ground	NE	60	150	2.2	4			1.4	Manually	Yes
	8.31	Ground	NW	55	137	2.2	4			1.4	Manually	Yes
	8.32	Ground	NW	55	137	2.2	4			1.4	Manually	Yes

¹Orientation.²Volume(m³).³Window area (m²).⁴Number of windows.⁵Minimum height of window sill (m).

the building. (2) Mild climates can reduce the biased impact of one extreme climate to let investigate window operation in NV buildings during both non-heating and heating seasons. This study was carried out in Coventry, West Midland from July 2017 until the end of May 2018. Both seasons were studied because variations in temperature and relative humidity would influence students' perception of the indoor environment.^{53,54} Measurements during schools' occupied time show that outdoor temperatures varied between 11.5–24.9°C with a mean of 18.1°C during non-heating seasons and changed between 3.5–14.2°C with a mean of 7.8°C during heating seasons. Outdoor variables were taken from Met office local weather stations⁵⁵ that were maximum 3 miles away from each study site.

2.2.2 | Buildings

In this study, 29 NV classrooms were selected in eight primary schools that comply with the following five criteria. (1) Selected schools are naturally ventilated since the main source of ventilation in most schools in the UK is windows. Furthermore, variations in temperature, relative humidity, and indoor pollutants from mechanical ventilation and air-conditioning systems^{53,54} can impact children's perception of IAQ. (2) Schools were selected in quiet areas with a considerable distance to the main road to not restrict window operation due to high background noise level as recommended by Building Bulletin 93: Acoustic Design of Schools to facilitate natural ventilation.⁵⁶ The regional Road Noise, LAeq 16h, is less than 55 dB in all selected schools according to England Noise Map Viewer.⁵⁷ (3) Schools were also selected in low-polluted areas to not restrict window operation, as recommended by CIBSE TM 21: Minimizing pollution at air intakes.⁵⁸ Schools were selected in areas with low Daily Air Quality Index (DAQI) according to Air pollution Forecast provided by the Met Office.⁵⁹ (4) Buildings were selected with different architectural features as studies have shown that buildings' design affects IAQ.^{24,38,60} Classroom's architectural features are shown in Table 1; classroom area (50–70 m²), volume (130–252 m³), window area (0–8 m²), number of windows (0–8), and the minimum height of windowsill (0.5–2.3 m). 5. Schools were selected among both renovated and existing buildings because buildings have different potentials for maintaining IAQ according to their age and design.^{42,60,61} Furthermore, the required IAQ is different for renovated and existing buildings.⁶² Among 29 classrooms, 13 classrooms are renovated and 16 classrooms are not.

2.2.3 | Occupants

It is important to select an age-group that has a good understanding of questionnaire structure and indoor environment. Among primary school students, children in their late middle childhood (9–11 YO) rather than their peers in early middle childhood (6–8 YO) were selected as the main respondents of this study because of their more developed literacy skills, cognitive abilities,⁶³ and attention span.⁶⁴

TABLE 2 Questions on indoor quality taken from the self-reported questionnaire designed by authors⁶⁵

Variables	Questions	Scales and coding				
Indoor Environment Quality	How do you feel now?	Cold (-2) <input type="checkbox"/>	Cool (-1) <input type="checkbox"/>	Fresh (2) <input type="checkbox"/>	OK (0) <input type="checkbox"/>	Warm (+1) <input type="checkbox"/>
	How is the air in the classroom now?	Very fresh (1) <input type="checkbox"/>			OK (3) <input type="checkbox"/>	Stuffy (4) <input type="checkbox"/>
	I like the air to be ... now.	Fresher (1) <input type="checkbox"/>			As it is (2) <input type="checkbox"/>	Very Stuffy (5) <input type="checkbox"/>
	Do you feel comfortable now?	I am comfortable (1) <input type="checkbox"/>		I am a little comfortable (2) <input type="checkbox"/>		I am not comfortable (3) <input type="checkbox"/>
	Do you feel tired now?	I am not tired now (1) <input type="checkbox"/>		I am a little tired now (2) <input type="checkbox"/>		I am tired now (3) <input type="checkbox"/>

Note: Worst judgment on IAQ = Vote 5 (very stuffy), worst judgment on comfort and tiredness level = Vote 3 (I am not comfortable, and I am tired now). Colors are designed based on children's perception of the votes. For example, red shows hotness and blue shows coldness.

They evaluate facts better,⁶⁴ which results in data validity and consistency of findings.⁶³ The gender ratio of surveyed girls (51%) and boys (49%) is approximately the same that can reduce bias and increase the credibility of results.⁶⁵

2.3 | Data acquisition

2.3.1 | Children's perception of indoor environment

This study acquires data on children's Air Sensation Votes (ASVs) and Thermal Sensation Votes (TSVs) through a self-reported questionnaire that was validated in an earlier study by authors,⁶⁵ Table 2. Children's perception of IAQ was questioned by "How is the air in the classroom now?" with a 5-point rating scale as "Very fresh, Fresh, OK, Stuffy and Very stuffy". This question is followed by another question to find out if they want the air to be "Fresher" or "As it is." Several other studies confirm that CO₂ concentrations determine children's perception of air freshness and stuffiness.^{33,66,67} To evaluate how Thermal Sensation Votes (TSVs) affect ASVs, children were surveyed on the thermal environment by "How do you feel now?" with a 5-point rating scale as "Cold, Cool, OK, Warm, Hot." To discover how comfort and tiredness levels are related to ASVs, two other questions, "Do you feel comfortable now?/Do you feel tired now?" were administrated to children by 3-point rating scales, Table 2.

According to Building Bulletin 101 (2018), the internal air quality in schools is determined largely by odor (from people and materials) and CO₂ levels, rather than any other pollutants.⁸ Therefore, during the pilot study, another question was designed for evaluating children's perception of IAQ; "Is your classroom smelly now?".⁶⁵ However, this question was removed from the questionnaire during the validation process⁵³ since no correlation was found between CO₂ levels and answers to this question. This is mainly because occupants already in the room will not be aware of odor, as a reaction to odor is immediate and olfactory sense rapidly adjusts to odor.⁶⁸ Studies have shown that CO₂ concentrations better account for children's perception of air freshness^{66,67} than children's perception of smell.⁶⁵

Children were usually asked to fill out the paper-based questionnaire at the end of morning and afternoon sessions because the end of sessions has the poorest conditions in terms of IAQ due to accumulation of stale air.²¹ In total, questionnaires were filled out on 52 different morning and afternoon sessions. Goto et al (2002)⁶⁹ suggest that occupants should maintain a stable activity level at least 30 minutes before filling out the questionnaire. Therefore, the authors made sure that children maintained sedentary activities (reading and writing) at least 30 minutes before filling out the questionnaires. Running surveys resulted in observing 805 children and collecting 1390 questionnaires, Table 3.

TABLE 3 The number of schools, classrooms, and children observed

School Number	Date	Number of classrooms	Number of surveyed & observed children	Number of collected questionnaires
School 1	July 17-21, 2017	5	130	210
School 2	September 21-27, 2017	4	110	195
School 3	October 29-31, 2017	3	65	115
School 4	November 21-24, 2017	3	85	115
School 5	Jan 29-Feb 02, 2018	5	145	290
School 6	Feb 12-16, 2018	5	85	140
School 7	April 17-19, 2018	3	80	165
School 8	May 22-25, 2018	4	105	160
Total	July 2017- May 2018	32	805	1390

Categories	IAQ standard	Expected percentage dissatisfied	Range of CO ₂ levels	Total CO ₂ level based on outdoor CO ₂ of 400 ppm
Category I	High	<15	<400	<800
Category II	Medium	15-20	400-600	800-1000
Category III	Moderate	20-30	600-1000	1000-1400
Category IV	Low	>30	>1000	>1400

TABLE 4 CO₂ levels and expected percentage dissatisfied by EN 13779:2007 for each category of IAQ⁶²

2.3.2 | Environmental measurements

Environmental variables affecting IEQ and comfort were recorded at 5-minute intervals; however, environmental variables recorded at the time of children's filling out the questionnaire are evaluated in this study. Environmental variables were recorded at 5-minute intervals by multi-functional SWEMA equipment, standalone data loggers, and CO₂ meter (TGE-0011, accuracy: $\pm 50 + 2\%$). Measurement station was located away from the main airflows (eg, windows), away from heat sources (eg, projectors), and also away from sun patches at a height of 1.1 m as recommended by ISO 7726.⁷⁰ Equipment was placed within the vicinity of children's desks without impairing their visual access and seating arrangement. The instruments were set up in the classrooms before children's arrival in the morning so that instruments acclimatize to the classrooms' environment before reading.⁴⁷

2.4 | IAQ standards

The European standard of EN 13779:2007⁶² recommends IAQ values and expected percentage dissatisfied in four different building categories, Table 4⁶²: (I) high level of expectation for spaces occupied by very sensitive people with special requirements, (II) normal level of expectation for new buildings and renovations, (III) moderate level of expectation for existing buildings, and (IV) low level of expectation only acceptable for a short period.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standard 62 recommends CO₂

level of 1000 ppm for classrooms,¹⁴ which is similar to that for Category II buildings for new and renovated buildings.

2.5 | Statistical analysis

To decide on the most appropriate statistical tests, parametric and non-parametric tests are defined.

Parametric tests can only be used when data fulfill these three conditions: (1) the level or scale of measurement is of equal interval or ratio scaling, (2) the distribution of the population is normal, and (3) the variances of both variables are equal.^{71,72}

To check the normality of the interval-scale data, histograms, Kolmogorov-Smirnov/Shapiro-Wilk's tests and QQ plots are applied.⁷³ In histograms, the normally distributed data peak in the middle and are symmetrical about the mean (bell-shaped)⁷³; however, it does not need to be perfectly normally distributed.⁷⁴ For Kolmogorov-Smirnov/Shapiro-Wilk's tests, normality tests are unlikely to detect non-normality for small sample sizes ($n < 20$) and are too sensitive for larger sample sizes ($n > 50$).⁷³ In QQ plots, the points will be close to the line for normally distributed data.⁷⁴ Because Kolmogorov-Smirnov/Shapiro-Wilk's tests are sensitive to outliers, histograms for large samples and QQ plots for small samples can be used.⁷⁴ To check homogeneity of variance, Levene's test (part of standard SPSS output) can be used.⁷⁴

In this study, histograms and Levene's tests are used to check the distribution and variance of the dependent variable of air sensation votes (ASVs). Results of this study show that air sensation votes, as

dependent in this study, are approximately normal (bell-shaped), as shown in Figure 1; however, Levene's test shows that variances are not equal, $[F(4, 1354) = 14.7, P = .000]$. The data were analyzed using the Statistical Package for Social Science (SPSS).⁷⁵

Statistical analysis in the following is categorized into four main groups: (1) descriptive, (2) correlational, (3) predictive, and (4) group differences (cause and effect). Table 5 shows a summary of tests done in this study based on the type of dependent and independent variables.

2.5.1 | Descriptive statistics

Descriptive statistics such as (minimum, maximum, mean, and standard deviation) can describe normal distribution of variables.⁷⁴ In this study, descriptive statistics are used to describe the dependent variable of ASVs which is normally distributed.

2.5.2 | Correlational

Correlation indicates both the strength and direction of the relationship between a pair of variables.^{71,72} It is assumed that higher correlation coefficient values and smaller associated P values imply a stronger correlation.⁷⁶ Spearman's correlation is a non-parametric measure used for ordinal/interval and skewed data to show the strength of the relationship.⁷¹⁻⁷³

2.5.3 | Predictive

Regression explains how variables are related and it predicts dependent variable (y) given the independent variable (x),⁷⁴ ($y = a + bx + e$, $R^2 = n$). The R^2 value shows the proportion of the variation in the dependent variable which is explained by the model.^{71,72,74} In this

study, correlations and regressions are used to show how ASVs are related to T_{op} and CO_2 levels, Table 5.

2.6 | Group differences

Tests of group differences are used to determine whether the groups are the same or not.^{71,77} Chi-square test is used to compare proportions between two or more independent groups,^{15,71-73} and Kruskal-Wallis test is used to compare the medians between groups.⁷¹⁻⁷³ In this study, chi-square and Kruskal-Wallis tests are used to show how frequency and median of ASVs change in different categories of TSVs, IAQ, operative temperature (T_{op}), and tiredness, Table 5.

3 | RESULTS AND DISCUSSION

The study provides an overview of the recorded data on children's perception of the indoor environment and indoor environmental conditions. The first part of the study shows factors affecting ASVs including physical parameters (such as CO_2 levels, operative temperature, and humidity) and thermal sensation. The second part of the study shows factors that are affected by ASVs such as comfort and tiredness levels, Figure 2.

3.1 | Overview of the recorded data

• Perception of Indoor Environment:

The frequency of children's ASVs (%) and Air Preference Votes (APVs) during different seasons is shown in Figure 3. This figure shows that proportion of "OK" votes is the highest (40.3%), followed by "fresh or very fresh" votes (36.2%) and then "stuffy or very stuffy" votes (23.5%). The frequency (%) of comfort and tiredness votes during different seasons is shown in Figure 4.

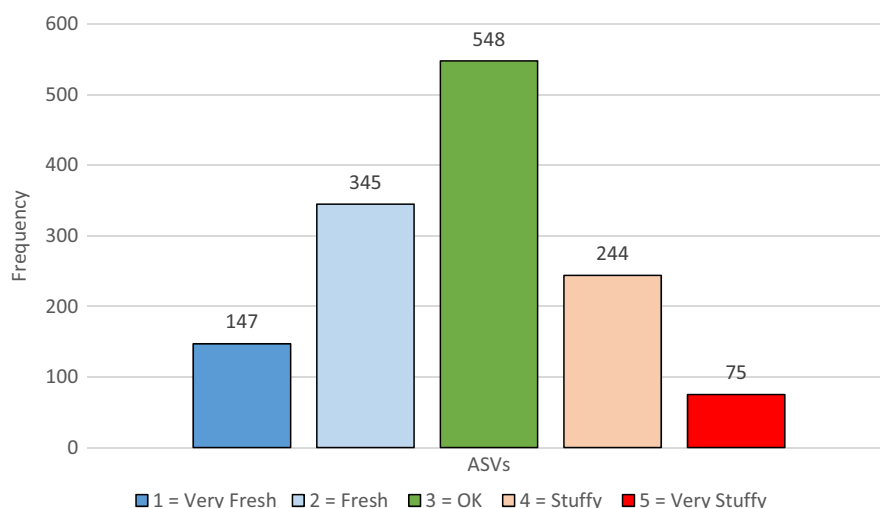
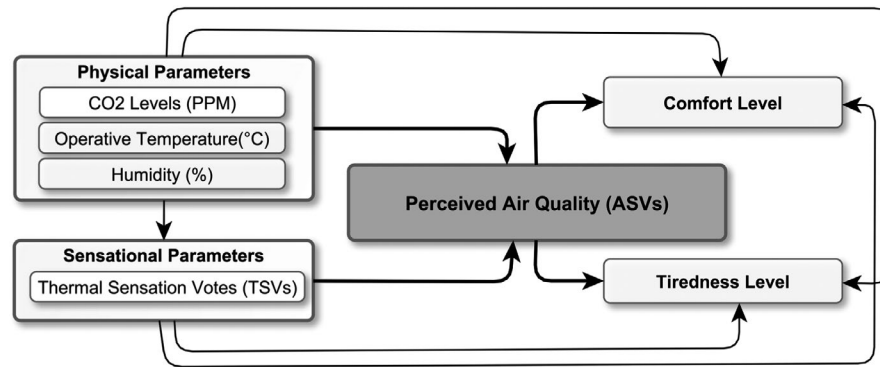
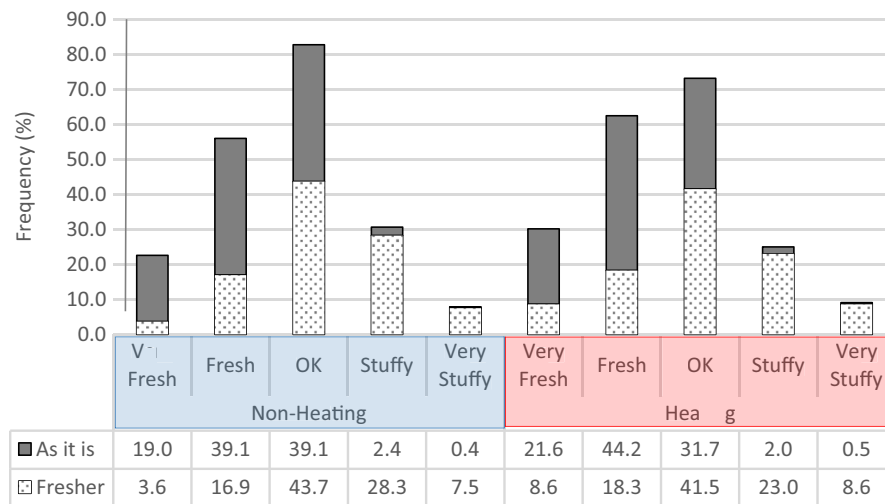


FIGURE 1 Normal distribution of ASVs

TABLE 5 Summary of all tests in this study

Variables			Variables in this Study	
Independent (IV)	Dependent (DV)	Corresponding Test	Dependent	Independent
1 interval IV	Ordinal or interval	Non-parametric Spearman correlation ⁷¹⁻⁷³	ASVs	CO ₂ levels T _{op}
1 IV with 2 or more groups	Ordinal or interval	Non-parametric Kruskal-Wallis test ⁷¹⁻⁷³	ASVs	TSVs
	Categorical	Non-parametric chi-square test ^{71,72}	ASVs	Different Cat of IAQ
				Different Cat of T _{op} Different Cat of Tiredness

**FIGURE 2** Classification of results and findings**FIGURE 3** Frequency (%) of ASVs and APVs during different seasons

ASVs and APVs during two seasons

Fresher
 As it is

As can be seen in Figure 4, “comfortable” votes are the highest (51.4%), followed by “a little comfortable” (34.7%) and “not comfortable” (13.9%). Similarly, “a little tired” votes are the highest (40.8%), followed by “tired” votes (33.8%) and “not-tired” (25.4%) votes, Figure 4.

• Indoor Environmental Conditions:

Descriptive statistics of environmental variables *at the time of filling out questionnaires* are presented in Table 6. Mean CO₂ level is higher during heating seasons (1310 ppm) than that during

non-heating seasons (1180 ppm). Maximum air velocity is below 0.1 m/s in this study; therefore, operative temperature (T_{op}) was calculated based on the average of indoor air temperature and radiant temperature.^{47,78} Mean operative temperature and humidity during non-heating seasons (24.2°C and 50.9%) are higher than those during heating seasons (22.8°C and 37.3%).

Figure 5 shows frequency (%) of “at-the-time CO₂ levels” in each category of IAQ during non-heating and heating seasons. Measurements of “at-the-time CO₂ levels” are mostly distributed in categories III and IV and CO₂ levels in Cat I are only recorded during non-heating seasons, Figure 5.

FIGURE 4 Frequency (%) of comfort and tiredness votes during different seasons

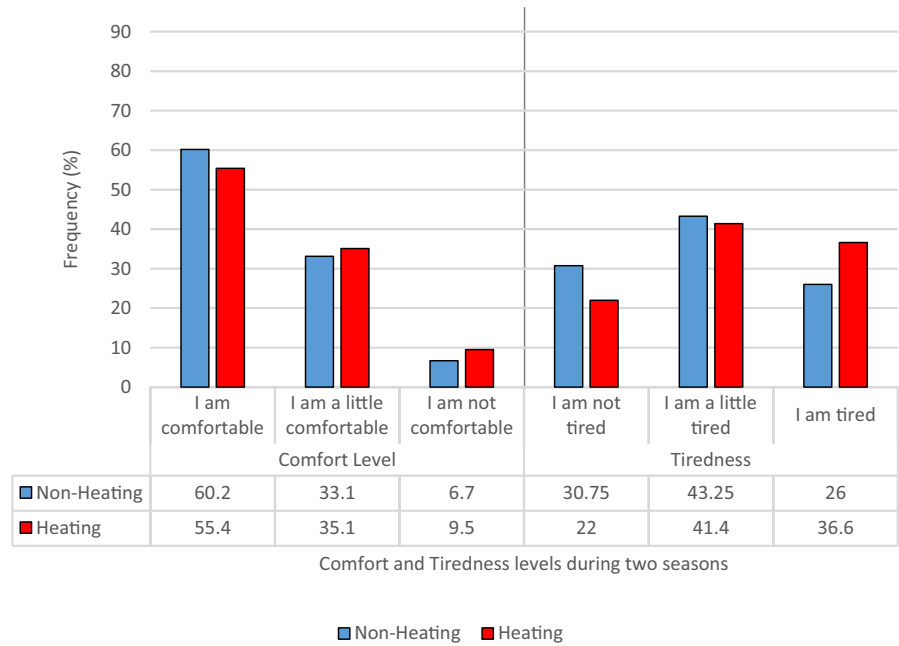


TABLE 6 Descriptive statistics of environmental variables at the time of filling out the questionnaire

Season	Parameters	Minimum	Maximum	Mean	SD
Non-heating	CO ₂ level (ppm)	662	3277	1180	488
	Air velocity (m/s)	0.00	0.1	0.08	0.05
	Operative temperature (°C)	19.0	28.1	24.2	2.1
	Relative humidity (RH)	38.3	66.6	50.9	7.8
Heating	CO ₂ level (ppm)	842	2106	1310	351
	Air velocity (m/s)	0.00	0.09	0.05	0.03
	Operative temperature (°C)	18.9	26.8	22.8	1.7
	Relative humidity (RH)	25.8	53.4	37.3	7.4

Table 7 shows mean operative temperatures and their standard deviations (SD) in each category of IAQ. As can be seen in Table 7, mean operative temperature and SD are higher when CO₂ levels are lower than 800 ppm (Category I) compared to other categories.

3.2 | The impact of CO₂ levels on ASVs

The impact of CO₂ levels on ASVs is investigated by predicting the strength of the relationship (correlations), degree of variations (regressions), and predicted percentage dissatisfied (PPD).

3.2.1 | Strength of relationship (Correlations)

CO₂ levels affect occupants' perceived IAQ^{19,28} and determine occupants' perception of air freshness and stuffiness.^{66,67} Results of this study, using Spearman correlation coefficient test, show that children' ASVs and CO₂ levels at the time of filling out the questionnaire are significantly correlated during non-heating seasons (Spearman correlation coefficient = 0.17, $P < .001$); however, the correlation is

less significant during heating seasons (Spearman correlation coefficient = 0.10, $P < .01$). CO₂ measurements are recorded at 5-min intervals in this study; therefore, "at-the-time CO₂ level" refers to the average CO₂ levels during the last 5 minutes. Correlations suggest that the strength of the relationship between CO₂ levels and ASVs is higher during non-heating (17%) than heating seasons (10%).

Correlations between ASVs and CO₂ levels were compared with the average of CO₂ levels during the last 10 and 15 minutes of the survey to estimate which range of CO₂ better indicates children's perception of IAQ, Table 8. During non-heating seasons, the correlation between ASVs and 5-minute CO₂ levels (correlation coefficient = 0.17) is higher than that with an average of 10-minute (correlation coefficient = 0.15) or 15-minute (correlation coefficient = 0.14) CO₂ measurements. During heating seasons, the correlation between ASVs and 5-min CO₂ levels ($P = .01$, correlation coefficient = 0.10) is more significant than that with average of 10-minute CO₂ measurements ($P = .04$, correlation coefficient = 0.09) and it is not significant for 15-minute CO₂ ($P = .25 > 0.05$), Table 8. Children' ASVs and average CO₂ levels during the whole session were not correlated ($P = .41 > .05$). Correlation coefficient shows the strength of the relationship between a pair of variables^{71,72};

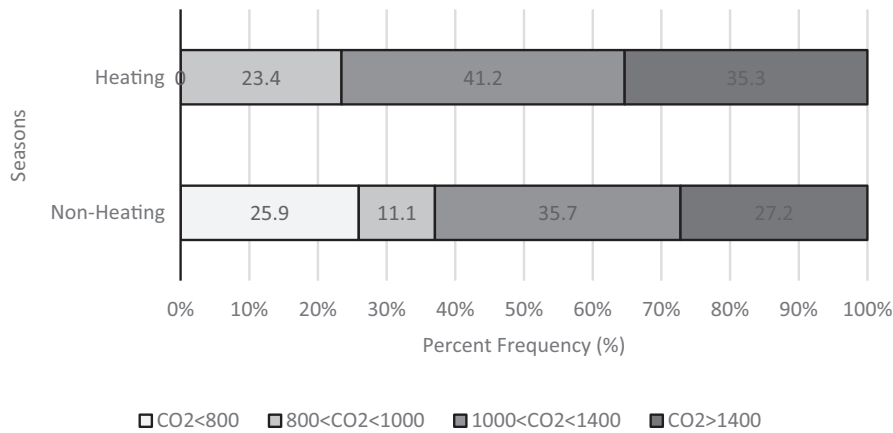


FIGURE 5 Frequency (%) of “at-the-time CO₂ levels” in each category of IAQ during different seasons

Categories	CO ₂ levels	Percent frequency (%)	T _{op} (Mean)	T _{op} (SD)
Category I	<800	14.7	23.31	3.01
Category II	800 < CO ₂ < 1000	16.5	22.93	2.26
Category III	1000 < CO ₂ < 1400	38.1	22.94	1.93
Category IV	CO ₂ > 1400	30.7	22.88	1.13

TABLE 7 Mean and SD of T_{op} in each category of IAQ

TABLE 8 The correlation between ASVs and 5-, 10-, and 15-min averages of CO₂ levels

Seasons	CO ₂ level	Sig. (2-tailed) with ASVs	Correlation with ASVs
Non-heating	5-min average	0.000	0.172***
	10-min average	0.000	0.148***
	15-min average	0.000	0.142***
Heating	5-min average	0.018	0.103*
	10-min average	0.042	0.089*
	15-min average	0.251	0.050

*P < .05.
 **P < .01.
 ***P < .001.

therefore, the last 5-minutes CO₂ measurements are used for further analysis due to a stronger relationship with ASVs.

The stronger relationship between ASVs and “5-minute CO₂ measurement” than “10 or 15 minutes CO₂ measurement” suggests that children get adapted to indoor CO₂ levels after 5 minutes. After 5-minute adaptation, children’s ASVs in this study are independent of CO₂ levels. Similar studies support that due to adaptation, ASVs show high acceptability, and adapted subjects would not distinguish between high and low levels of concentration.^{79,80} The study by Cain (1985) found that after 3 minutes of adaptation, perceived intensity reaches a stable level of 40% of the initial amount.⁸¹ Another study by Gunnarsen (1992) shows that 95% of the votes on IAQ change due to adaptation which took place within 6 minutes of exposure.⁷⁹ After 5 minutes, adapted votes that are independent of CO₂ levels

are obtained; therefore, the study uses at-the-time CO₂ levels (5-min measurement) for further analysis. Standards and regulations usually consider average CO₂ levels as an indicator of IAQ because concentrations are generally spatially non-uniform.²⁸ However, these results suggest that children’s instantaneous perception of IAQ is more related to CO₂ levels at the time of the survey. Therefore, children’s ASVs in short intervals should also be evaluated to have a better understanding of perceived IAQ.

3.2.2 | Degree of variations (regressions)

For each survey, the proportions of “very fresh/fresh” (ie, ASV = 1 or 2), “OK” (ie, ASV = 3), and “stuffy/very stuffy” (ie, ASV = 4 or 5) votes were calculated and plotted against CO₂ levels during non-heating and heating seasons, Figures 6 and 7. Similarly, the proportion of children who prefer the air quality to be “fresher” (ie, APV = 1) or “as it is” (ie, APV = 2) was calculated and plotted against CO₂ levels, Figures 6 and 7.

Non-heating seasons: As can be seen in Figure 6, by the increase in CO₂ levels, “fresh/very fresh” votes decrease, and “OK” and “stuffy/very stuffy” votes increase during non-heating seasons. Regressions in Figure 6 suggest that 33% variations in “fresh/very fresh” votes, 28% variations in “OK” votes and 5% variations in “stuffy/very stuffy” votes are explained by CO₂ levels. To predict how votes change by CO₂ changes, “slope” and “intercept” of each linear model are also considered, as suggested in other studies.^{71,72} Slopes in Figure 6 show that the rate at which CO₂ changes affect ASVs is highest for “fresh/very fresh” votes, then “OK” votes and then “stuffy/very stuffy” votes during non-heating seasons.

FIGURE 6 Proportions of ASVs and APVs by CO₂ levels during non-heating seasons

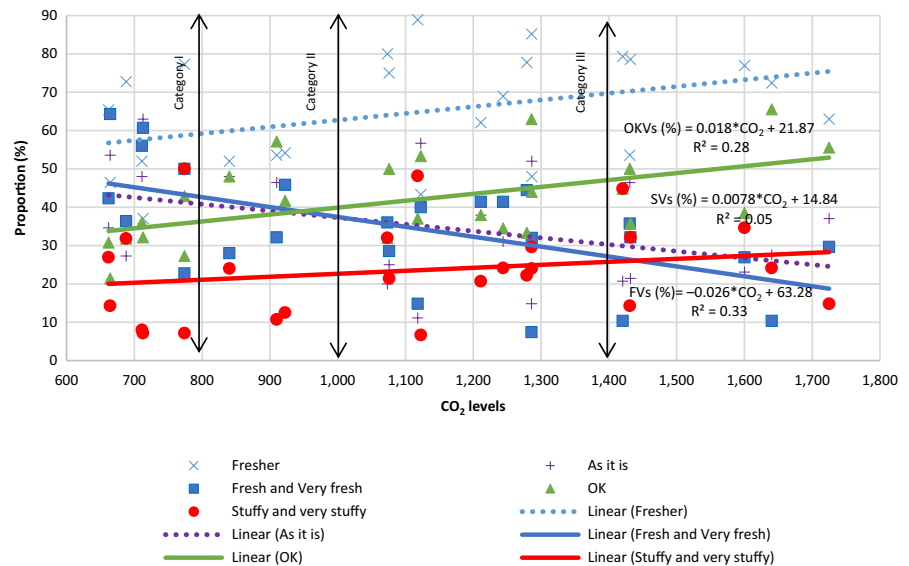


FIGURE 7 Proportions of ASVs and APVs by CO₂ levels during heating seasons

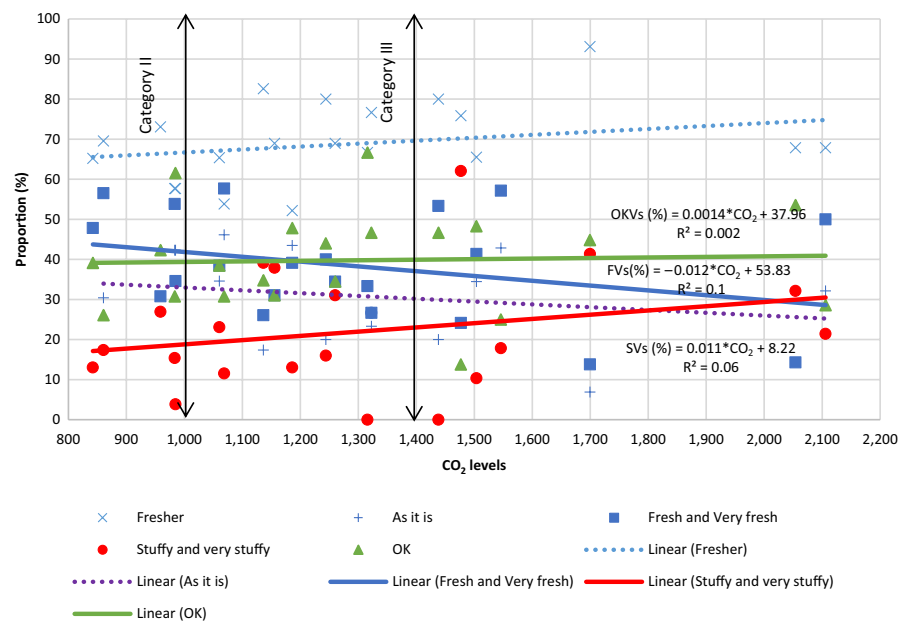


Figure 6 shows that “fresh/very fresh” line intersects with “OK” line at CO₂ level of 950 ppm and it intersects with “stuffy/very stuffy” line at CO₂ level of 1450 ppm. This indicates that at CO₂ = 950 ppm, the proportion of “fresh/very fresh” and “OK” votes is equal and at CO₂ level = 1450 ppm, the proportion of “fresh/very fresh” and “stuffy/very stuffy” votes is equal. When CO₂ > 950 ppm, the proportion of “OK” votes is more than “fresh/very fresh” votes, and when CO₂ > 1450 ppm, the proportion of “stuffy/very stuffy” votes is more than “fresh/very fresh” votes. This suggests that “at-the-time CO₂ levels” should not exceed 1450 ppm; otherwise, the proportion of “stuffy/very stuffy” votes would be more than “fresh/very fresh” votes. CO₂ level of 1450 ppm is close to the upper limit of Category III buildings which corresponds to a moderate level of expectation for existing buildings.

Heating Seasons: As can be seen in Figure 7, by the increase in CO₂ levels, “fresh/very fresh” votes decrease, “OK” votes do not change, and “stuffy/very stuffy” votes increase during non-heating seasons. Regressions in Figure 7 reflect that only 10% variations in “fresh/very fresh” votes, 6% variations in “stuffy/very stuffy” votes, and 2% variations in “OK” votes are explained by CO₂ levels. Slopes in Figure 7 show that the rate of CO₂ changes is highest for “fresh/very fresh” votes, then “stuffy/very stuffy” votes, and then “OK” votes during heating seasons. The graph shows that “fresh/very fresh” line intersects with “OK” line at CO₂ level = 1150 ppm and it intersects with “stuffy/very stuffy” line at CO₂ = 2000 ppm. This shows that at CO₂ = 1150 ppm, the proportion of “fresh/very fresh” and “OK” votes is equal and at CO₂ = 2000 ppm, the proportion of “fresh/very fresh” and “stuffy/very stuffy” votes is equal.

Comparing Figures 6 and 7 shows that the proportion of “OK” votes increases by the increase in CO_2 during non-heating seasons; however, they do not change significantly during the heating season. This suggests that “OK” votes do not show a fixed or recognized trend for acceptability on air sensation scale. On the other hand, “OK” votes on thermal sensation scale are perceived acceptable because thermal sensation scale is symmetrical with more acceptable votes in the middle and less acceptable ones at the ends. Air sensation scale has a direction from the acceptable to unacceptable votes, with “OK” votes in the middle as a transition point. Therefore, only “fresh/very fresh” and “stuffy/very stuffy” votes change by CO_2 variations.

3.2.3 | CO_2 levels and Predicted Percentage Dissatisfied (PPD)

European²¹ and ASHRAE standards¹⁴ suggest that for acceptable IAQ, the percentage of dissatisfaction among occupants should not be more than 20%.^{14,82-84} Maximum PPD of 20% regarding thermal comfort is generally acceptable; therefore, it is prudent to adopt a 20% PPD level regarding IAQ.²⁰

EN 13779:2007⁶² for categories I and II and ASHRAE standards¹⁴ recommend CO_2 levels below 1000 ppm for maintaining IAQ; this level is also recommended in several other studies.¹⁵ Therefore, PPD is calculated for CO_2 levels more than 1000 ppm or less than 1000 ppm, Figure 8. Results of this study show that when $\text{CO}_2 < 1000$ ppm, expected percentage dissatisfied (PPD) with IAQ is 17.4%. Two more studies confirm that the threshold for PPD of 20% is approximately 1000 ppm.²⁰ When $\text{CO}_2 > 1000$ ppm, “stuffy/very stuffy” votes increase around 9% and “fresh/very fresh” votes decrease around 13%. This means by keeping CO_2 levels below 1000 ppm, around 22% improvement in ASVs can be maintained. Furthermore, when $\text{CO}_2 < 1000$ ppm, “Fresh/Very Fresh” votes are 27% higher than “Stuffy/Very Stuffy” votes; however, this difference is only 5% when $\text{CO}_2 > 1000$ ppm.

3.3 | Impact of operative temperature and humidity on ASVs

Humphreys et al (2002) suggest that physical variables such as air temperature and relative humidity affect IAQ perception directly.⁸⁵ Wargocki and Wyon (2017) also show that the mechanisms that mediate the impacts of IAQ and thermal environment on performance are surprisingly similar.⁸⁶ To discover how operative temperature (T_{op}), humidity (RH%), and ASVs are related, correlation tests were run between ASVs, T_{op} , and RH%, Table 9. Previous studies have shown that lower humidity improves perceived IAQ^{28,81,87,88}; however, results of this study show that humidity does not affect children's ASVs ($P_{(NH)} = 0.072$ and $P_{(H)} = 0.46 > 0.05$), Table 9. This is mainly because children are not exposed to very low or very high humidity levels in this study (38%-66% during non-heating and 26%-53% during heating seasons), Table 6. It is also shown that humidity has a modest effect on thermal sensation and perceived IAQ for moderate environments ($<26^\circ\text{C}$)⁸⁹ activity levels (<2 met).^{21,89} As can be seen in Table 9, there is a correlation between CO_2 levels and humidity during non-heating (Spearman correlation coefficient = 0.11, $P < .005$) and heating seasons (Spearman correlation coefficient = 0.43, $P < .001$). This is mainly because relative humidity and CO_2 levels are both emanated through occupants' respiration and sweating, as suggested by Ghita and Catalina (2015)⁹⁰; therefore, relative humidity and CO_2 variations have similar patterns.

Results of this study show that operative temperature (T_{op}) is not correlated to children's ASVs during non-heating seasons ($P = .27 > .05$); however, it is significantly related to their ASVs during heating seasons (Spearman correlation coefficient = 0.15, $P < .001$), Table 9. During non-heating seasons, ASVs are correlated to CO_2 levels (Spearman correlation coefficient = 0.172, $P < .001$) and not to T_{op} ($P = .27 > 0.05$), Table 9. During heating seasons, ASVs are more correlated to T_{op} (Spearman correlation coefficient = 0.15, $P < .001$) compared to CO_2 levels (Spearman correlation coefficient = 0.1, $P < .05$), Table 9. To assure that

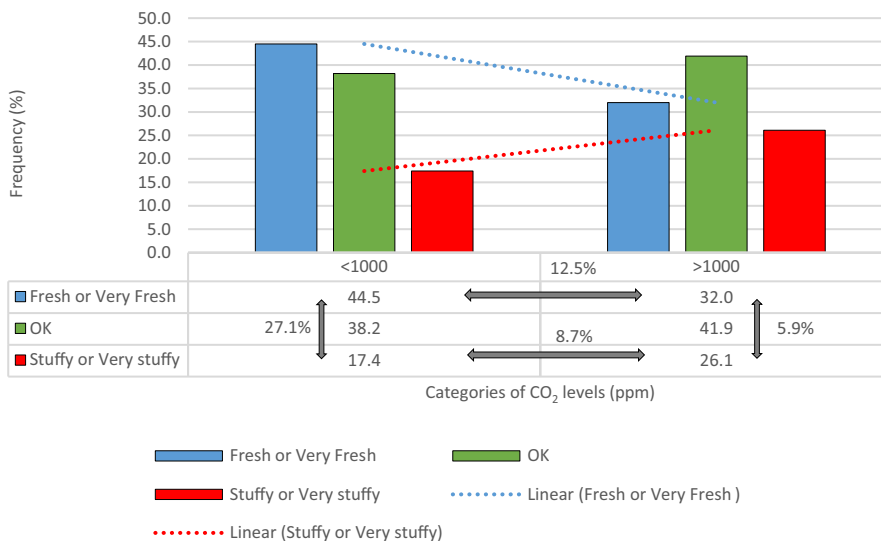
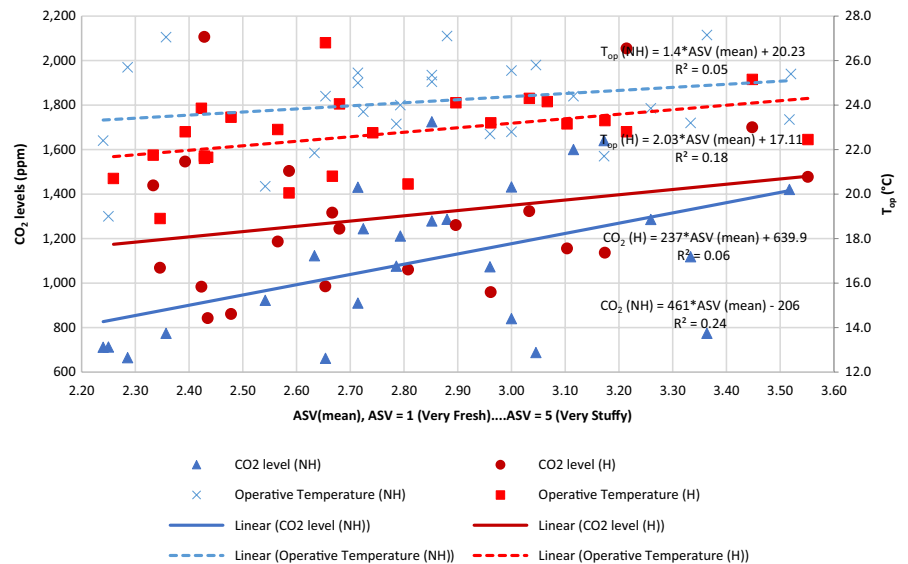


FIGURE 8 Frequency (%) of ASVs in each category of IAQ

TABLE 9 The correlation coefficient between parameters

Seasons	Parameters	ASVs		Operative temperature (T_{op})		Humidity (RH%)	
		Correlation	Sig.	Correlation	Sig.	Correlation	Sig.
Non-heating	ASVs	1.000	.	0.04	0.27	-0.067	0.072
	CO ₂ level	0.172***	0.000	-0.12***	0.002	0.11	0.004
Heating	ASVs	1.000	.	0.15***	0.000	-0.03	0.46
	CO ₂ level	0.10 ⁺	0.018	-0.10 ⁺	0.026	0.43	0.000

* $P < .05$.** $P < .01$.*** $P < .001$.**FIGURE 9** Impact of CO₂ levels (ppm) and T_{op} (°C) on mean ASVs

impact of T_{op} on ASVs is not influenced by CO₂ levels, the correlation between CO₂ levels and T_{op} is also investigated in Table 9. Results show that CO₂ and T_{op} have a negative correlation; suggesting that the impact of T_{op} on ASVs is not skewed by CO₂ levels. The negative correlation between CO₂ levels and T_{op} (°C) in this study is due to more open windows during non-heating seasons compared to heating seasons.

Children's mean ASVs are calculated for each survey based on scale codes in Table 2 (very fresh = 1, fresh = 2, OK = 3, stuffy = 4, very stuffy = 5). Figure 9 shows the relationship between mean ASVs for each survey, CO₂ levels (ppm), and T_{op} (°C) at the time of filling out the questionnaire. As can be seen in Figure 9, by an increase in CO₂ levels and T_{op} , mean ASVs increase. Regressions in Figure 9 suggest that 24% and 6% variations in ASVs are explained by CO₂ levels during non-heating and heating seasons, respectively. Similarly, 5% and 18% variations in ASVs are explained by T_{op} during non-heating and heating seasons, respectively. Results of the study show that for 1°C increase in T_{op} (°C), ASVs increase 0.8 and 0.5 points on the 5-point rating scale during non-heating and heating seasons. For 200 ppm increase in CO₂ levels, ASVs increase 0.45 and 0.85 points during non-heating and heating seasons. A similar study shows that by 1°C change in room temperature, average ASV

of university students changes 0.3-0.4 points on the 6-point rating scale.¹⁹

Results of this study show that lower temperatures improve children's perception of IAQ. Previous studies have also confirmed that lower temperature (keeping the air cool) improves perceived IAQ and higher temperatures degrade IAQ.^{28,30,81,87,91,92} Therefore, the air is perceived fresher at reduced temperatures and stuffier at higher temperatures. Temperature changes the energy content of the air and the cooling effect in the respiratory tract.⁸⁸ When the temperature is considerably lower than the mucosal temperature (30-32°C), the thermal sense is stimulated due to convective and evaporative cooling of the respiratory tract.¹⁵ When the respiratory cooling effect decreases to a certain level, the air is perceived very poor whether the air is clean or polluted.⁸⁸ A similar study shows that for the median indoor temperature of 22.31°C, students were totally satisfied with IAQ while for temperatures greater than 25°C, they were dissatisfied.³³ Thermal conditions can also affect IAQ indirectly by influencing emission sources and indoor concentrations of pollutants.¹²

Figure 10 shows that the impact of temperature on ASVs decreases with an increasing level of CO₂ concentration. As can be seen in Figure 10, when CO₂ level = 800 ppm, by 1°C decrease in temperature from 24.5°C to 23.5°C, children's ASVs change from

“stuffy/very stuffy” to “fresh/very fresh.” However, when CO_2 level > 1400 ppm, a decrease in temperature does not change or improve children's ASVs significantly. Figure 11 shows that the influence of CO_2 concentration on ASVs decreases with increasing temperature. As can be seen in Figure 11, when $T_{\text{op}} = 19^\circ\text{C}$, around 300 ppm decrease in CO_2 level from 1500 to 1200 ppm improves children's ASVs from “stuffy/very stuffy” to “fresh/very fresh.” However, when $T_{\text{op}} > 26^\circ\text{C}$, the decrease in CO_2 levels does not significantly improve children's ASVs.

This study shows that the impact of temperature on ASVs decreases with increasing CO_2 levels, and the influence of CO_2 concentration on ASVs decreases with increasing temperature. Both findings are supported in a similar study by Fang et al (1998)⁸⁸ on the impact of temperature and humidity on the perception of IAQ. These findings can be explained by two reasons; warm air can be interpreted stuffy and perceived unacceptable, whether the air is fresh or stuffy.⁸⁸ It is shown that temperature affects IAQ especially when the air is overheated.⁸⁸ Stuffy air can also be interpreted as warm in the respiratory tract and perceived unacceptable.^{88,93}

3.3.1 | Comfort temperature

An earlier study by authors shows that the upper limit of thermal comfort band for surveyed children is around 23°C .⁹⁴ Therefore, the frequency (%) of ASVs in two categories of operative temperature ($T_{\text{op}} < 23^\circ\text{C}$ and $T_{\text{op}} > 23^\circ\text{C}$) is investigated. The result of the chi-square test shows that there is a significant difference in the frequency of ASVs in two categories of operative temperatures [$\chi^2(2, N = 1359) = 19.9, P < .001$]. As can be seen in Figure 12, when $T_{\text{op}} < 23^\circ\text{C}$, “Fresh/Very Fresh” votes are around 9% higher and “Stuffy/very stuffy” votes are around 11% lower compared to when $T_{\text{op}} \geq 23^\circ\text{C}$. Therefore, around 20% improvement in ASVs can

be observed when T_{op} is within or lower than children's thermal comfort band. Furthermore, when $T_{\text{op}} < 23^\circ\text{C}$, “Fresh/Very Fresh” votes are 25% higher than “Stuffy/Very Stuffy” votes; however, this difference is only 5% when $T_{\text{op}} > 23^\circ\text{C}$.

To ensure that children's improved perception of IAQ is also impacted by lower temperatures and not merely by air change rates, ventilation rates, and CO_2 levels, the study considers the correlation between operative temperatures, air change rates, and ventilation rates. An earlier study by authors⁹⁵ evaluates ventilation rates on the same classrooms from the transient mass balance method. Results show that T_{op} is correlated with ACRs (Spearman correlation coefficient = 0.20, $P < .05$) and VRs (Spearman correlation coefficient = 0.29, $P < .001$). The positive correlation suggests that when T_{op} is higher, ACRs and VRs are also higher.⁹⁵ This indicates that by the increase of T_{op} , there is a higher tendency to open windows which in turn increases VRs, as supported in several other studies.^{22,42}

This finding rejects the hypothesis that lower temperatures improve children's perception of IAQ through higher ventilation rates.

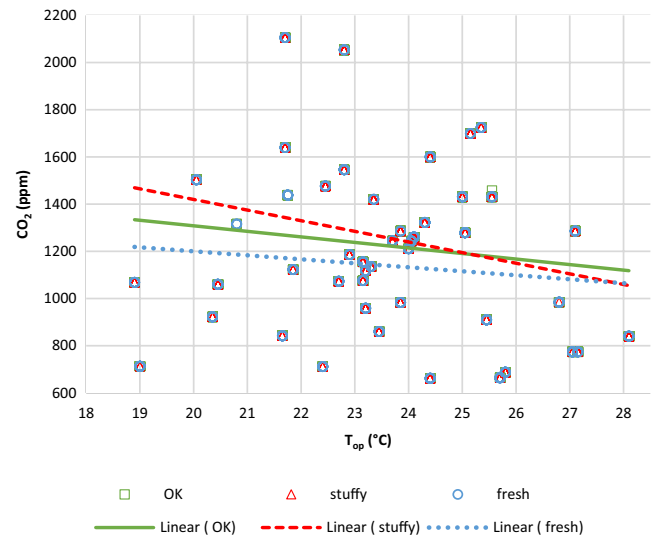


FIGURE 11 Impact of CO_2 levels on ASVs with increasing temperature

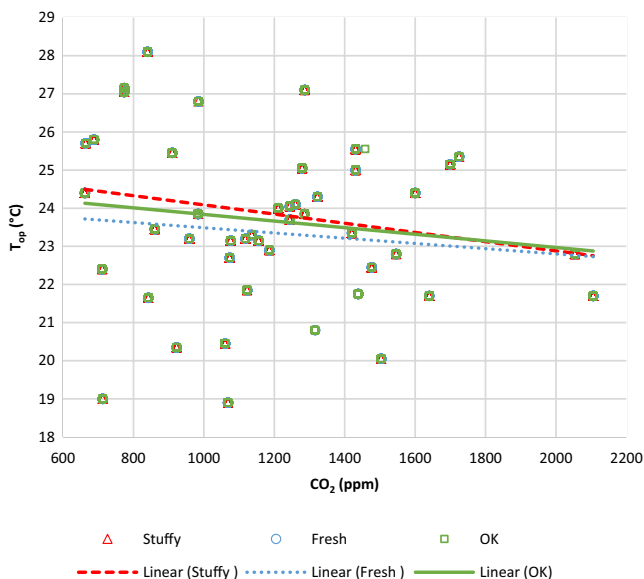


FIGURE 10 Impact of temperature on ASVs with increasing CO_2 level

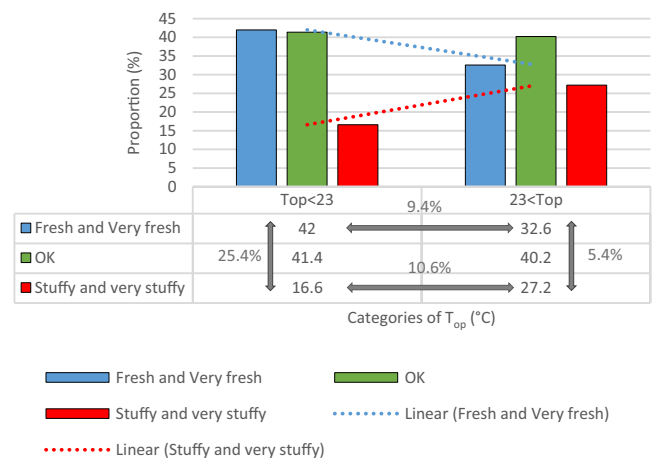


FIGURE 12 The effect of T_{op} ($^\circ\text{C}$) on ASVs

The study highlights that lower temperatures improve children's perception of IAQ independent of ventilation rates.

3.4 | Impact of thermal perception on ASVs

The study shows the effect of TSVs and TPVs on ASVs in boxplots, Figures 13 and 14. Results of Kruskal-Wallis H test show that there is a statistically significant difference in mean and median of ASVs between different groups of TSVs during non-heating ($\chi^2(4) = 26.89$, $P = .000$) and heating ($\chi^2(4) = 58.97$, $P = .000$) seasons. Similarly, there is a statistically significant difference in ASVs between different groups of TPVs during non-heating ($\chi^2(4) = 62.13$, $P = .000$) and heating ($\chi^2(4) = 61.2$, $P = .000$) seasons.

Figure 13 shows that children's ASVs are oriented toward stuffy/very stuffy votes when children feel hot [$ASV_{(mean)} = 3.3$ -3.5] and cold [$ASV_{(mean)} = 2.6$ -3.2]. This finding is confirmed by Humphreys et al (2002) that show when occupants are uncomfortably warm, they perceive IAQ poorly.⁸⁵ The most favorable ASVs [$ASV_{(mean)} = 2.4$ -2.5] are given when children feel "cool" during both seasons. Figure 14 shows that when children have "cooler" preference, they give the least favorable ASVs [$ASV_{(mean)} = 3.4$]; however, when they have "as it is" preference, they give the most favorable ASVs [$ASV_{(mean)} = 2.4$ -2.5]. Humphreys et al (2002) also support that respondents give the most favorable ASVs when they require no change in the thermal environment.⁸⁵ Therefore, in this study with the focus on UK children, the most favorable ASVs are given when children feel "cool" and have "as it is" preference. However, these results may be different in another climate.

In Table 10, *crosstabs* were created by using TSVs, TPVs, and ASVs. Among children who feel "hot," nearly half of them (47%) find the classroom "stuffy/very stuffy," while less than a quarter (23%) find the classroom "fresh/very fresh." Among children who feel "cool," more than half of them (53%) find the classroom "fresh/very fresh" and only 13% find the classroom "stuffy/very stuffy"; "fresh/very fresh" votes are 4 times more than "stuffy/very stuffy" votes, Table 10.

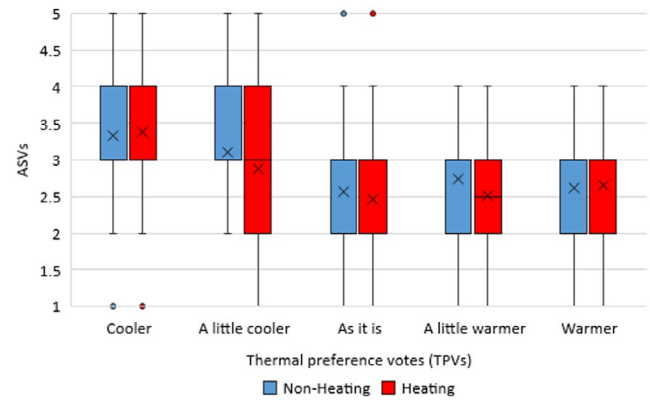


FIGURE 14 ASVs change within different categories of TPVs

Among children who have "cooler" preference, 23% find the classroom "fresh/very fresh" and 48% find the classroom "stuffy/very stuffy"; "stuffy/very stuffy" votes are more than two times "fresh/very fresh" votes, Table 10. Among children who prefer the classroom "as it is," 46% find the classroom "fresh/very fresh" and 8% find the classroom "stuffy/very stuffy"; "fresh/very fresh" votes are 5.8 times more than "stuffy/very stuffy" votes, Table 10. This indicates the impact of TSVs and TPVs on ASVs; when children are more satisfied with their thermal environment, they give more favorable ASVs.

3.5 | Integration

Results of this study show that by keeping CO_2 levels below 1000 ppm, ASVs improve by 23% (Refer to 3.1.3). Furthermore, by keeping operative temperatures within or below thermal comfort band ($T_{op} < 23^\circ C$ in this study), ASVs improve by around 20%. To integrate the impact of both T_{op} and CO_2 on ASVs, the proportion of children in each category of ASVs based on T_{op} and CO_2 is presented in Table 11.

According to Table 11, when $CO_2 < 1000$ ppm and $T_{op} < 23^\circ C$ (operative temperature is below the upper limit of thermal comfort

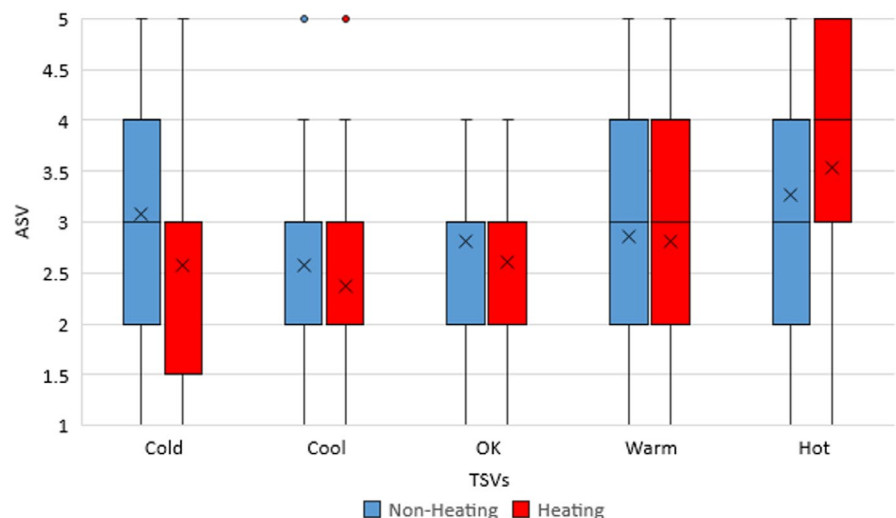


FIGURE 13 ASVs change within different categories of TSVs

TABLE 10 Frequency of TSVs and TPVs in each category of ASVs

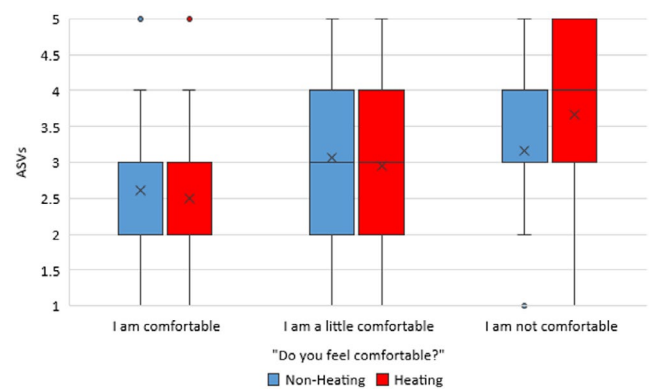
TSVs/TPVs		Air quality							
		Very fresh		Fresh		Stuffy		Very stuffy	
		Number	%	Number	%	Number	%	Number	%
TSVs	Cold	12	21.8	8	14.5	9	16.4	6	10.9
	Cool	30	15.0	75	37.5	22	11.0	4	2.0
	OK	44	8.9	133	26.8	66	13.3	7	1.4
	Warm	47	11.7	96	23.8	97	24.1	13	3.2
	Hot	14	6.9	33	16.2	50	24.5	45	22.1
TPVs	Cooler	24	9.7	34	13.7	69	27.8	50	20.2
	A little cooler	24	6.9	72	20.8	95	27.5	11	3.2
	As it is	52	12.0	146	33.6	34	7.8	3	0.7
	A little warmer	26	11.7	69	30.9	29	13.0	6	2.7
	Warmer	21	19.6	24	22.4	17	15.9	5	4.7

TABLE 11 Frequency (%) of children's ASVs based on T_{op} and CO_2

CO_2 level (ppm)	Top	ASVs	Percent (%)
<1000	Top < 23°C	Fresh or very fresh	53.0
		OK	37.0
		Stuffy or very stuffy	10.0
	Top > 23°C	Fresh or very fresh	41.4
		OK	38.6
		Stuffy or very stuffy	20.0
>1000	Top < 23°C	Fresh or very fresh	36.7
		OK	41.4
		Stuffy or very stuffy	21.9
	Top > 23°C	Fresh or very fresh	28.7
		OK	42.2
		Stuffy or very stuffy	29.1

band), only 10% of children find the classroom "stuffy/very stuffy," which is lower than PPD recommended by EN 15251²¹ for Category I buildings. A similar study¹⁵ estimates that keeping $CO_2 < 1000$ ppm and $T_{op} < 22^\circ C$ can reduce PPD to 15%.¹⁵ Table 11 shows that when $CO_2 < 1000$ ppm and $T_{op} > 23^\circ C$, PPD increases to 20%. Another study¹⁵ estimates that when $CO_2 < 1000$ ppm and $T_{op} > 26^\circ C$, PPD will rise to 25%.¹⁵ Table 11 shows when $CO_2 > 1000$ ppm and $T_{op} > 23^\circ C$, 29.1% of children find the classroom "stuffy/very stuffy." When " $CO_2 < 1000$ ppm & $T_{op} < 23^\circ C$ " compared to when " $CO_2 > 1000$ ppm & $T_{op} > 23^\circ C$," "stuffy/very stuffy" votes are 19% less and "fresh/very fresh" votes are 24% more (43% improvements on ASVs).

Improving ASVs by 43% is hard to achieve just by lowering CO_2 levels and increasing ventilation rates; therefore, decreasing operative temperatures within thermal comfort band can also help to improve children's perception of IAQ. The study by

**FIGURE 15** ASV changes in different comfort groups

Bakó-Biró et al (2012) recommends UK schools managers to consider CO_2 , temperature, and humidity for maintaining IAQ, to keep temperatures within comfortable ranges [$20-22^\circ C$ during winter] and [$22-24^\circ C$ during summer] and humidity levels below 60% during winter time but preferably above 40%.⁹⁶ The study by Chatzidiakou et al (2015) confirms the need for an integrated approach providing simultaneously adequate IAQ and thermal comfort¹⁵ to improve the perception of IAQ. There is evidence that in case of insufficient cooling, increasing ventilation rate would be a waste of energy without any improvement in environment; however, decreasing air temperature up to the comfort threshold would succeed to provide a more pleasant perception of IAQ.⁸⁸ Fanger (1998) suggests ventilation standards such as ASHRAE do not consider the impact of temperature and humidity on perceived IAQ.⁸⁸ The review by Salthammer et al (2016) shows that poor IAQ in schools can be related to lack of budgets for local administrative bodies and inefficiency of regulations for better IAQ.⁹⁷ Results of this study also suggest that standards and regulations should consider the integrated impact of both temperature and CO_2 levels on perceived IAQ.

FIGURE 16 The combined effect of ASVs and TSVs on different comfort levels

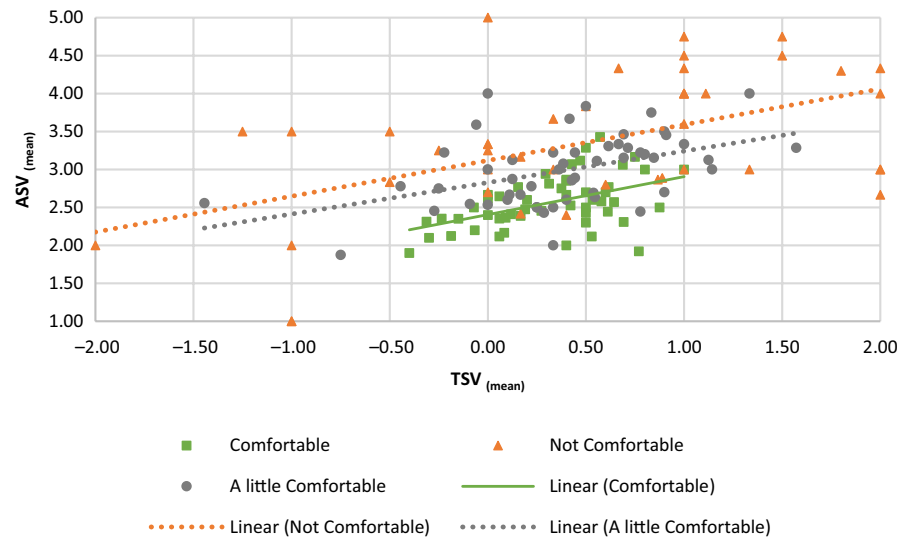
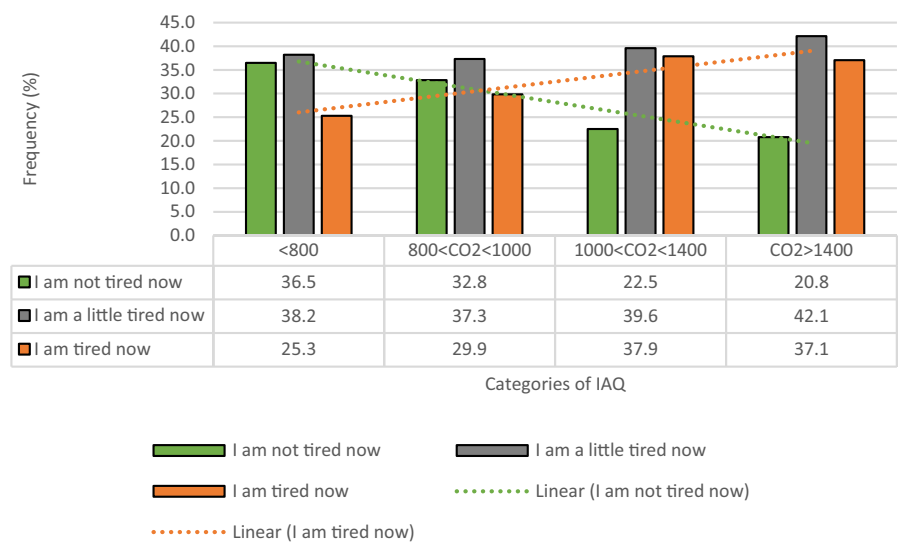


FIGURE 17 Frequency (%) of children in each group of tiredness for IAQ categories



3.6 | The impact of TSVs and ASVs on overall comfort

The study examines the effect of ASVs on different comfort groups as boxplots in Figure 15. Results of Kruskal-Wallis H test show that there is a statistically significant difference in mean and median of ASVs between different comfort groups during non-heating ($\chi^2(4) = 48.5, P = .000$) and heating ($\chi^2(4) = 104.5, P = .000$) seasons. Results show that when children are comfortable, mean ASVs are the most favorable ($ASV_{NH} = 2.6, ASV_H = 2.4$) and when children are not comfortable, mean ASVs are the least favorable ($ASV_{NH} = 3.2, ASV_H = 3.7$), Figure 15.

To examine the combined effect of ASVs and TSVs on comfort level, classrooms' mean ASVs and TSVs for each comfort group are presented in Figure 16. As can be seen in Figure 16, range of TSVs and ASVs for "comfortable" children is narrower than that for "a little comfortable" and "uncomfortable" children. Figure 16 shows that TSVs range from "-0.4 to +1" for comfortable votes, while they range from "-2 to +2" for uncomfortable votes. The difference between the

range of TSVs for comfortable and uncomfortable votes is 2.6 [(-2 to 2) - (-0.4 to 1)]. On the other hand, ASVs range from "+2.2 to +2.9" for comfortable votes, while they range from "+2.2 to +4" for uncomfortable votes. The difference between the range of ASVs for comfortable and not comfortable votes is 1.1 [(4-2.2) - (2.9-2.2)]. This suggests that changes in TSVs compared to ASVs are more significant in different comfort groups.

3.7 | Impact of CO₂ levels, ASVs, and TSVs on Tiredness

The frequency (%) of children in each group of tiredness for different IAQ categories is depicted in Figure 17. The result of chi-square test shows that there is a significant difference in frequency of (%) of tiredness groups in four categories of IAQ [$\chi^2(6, N = 1216) = 26.2, P < .001$]. Figure 17 shows that as classrooms' IAQ deteriorates from Category I to IV, the proportion of children feeling not tired decreases around 16% and the proportion of children feeling tired

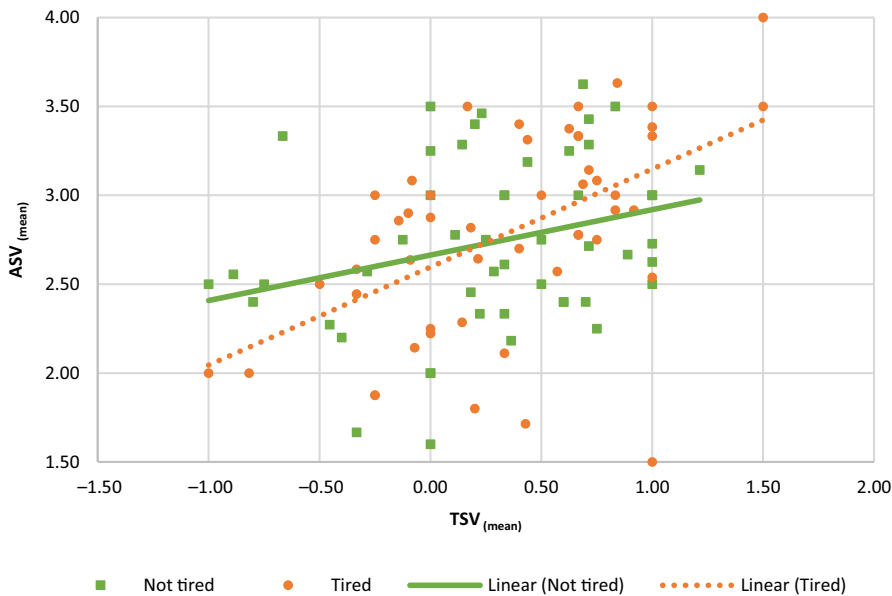


FIGURE 18 The combined effect of ASVs and TSVs on different levels of tiredness

increases around 12%. In total, by improving classrooms' IAQ from Category IV to I, 28% of tiredness votes can be improved.

To examine the combined effect of ASVs and TSVs on tiredness level, classrooms' mean ASVs and TSVs for each tiredness group are presented in Figure 18. As shown in Figure 18, TSVs range from "−1 to +1.25" for the "not-tired" group, while it ranges from "−1 to +1.5" for the "tired" group. The difference between ranges of TSVs for tired and not-tired groups is 0.25 $[(-1 \text{ to } 1.5) - (-1 \text{ to } 1.25)]$. On the other hand, ASVs range from "+2.5 to +3" for the "not-tired" group, while they range from "+2 to +3.5" for the "tired" group. The difference between the range of ASVs for "not-tired" and "tired" groups is 1.1 $[(3.5-2) - (3-2.5)]$. This suggests that changes in ASVs compared to TSVs are more significant in different groups of tiredness.

This study shows that by the increase in CO_2 levels, tiredness levels increase. Previous studies have also shown that higher CO_2 levels are related to higher tiredness^{29,65,96} and discomfort^{7,65} levels. It is important to reduce the CO_2 level before discomfort and tiredness levels set in. An earlier study by authors using the same data set⁶⁵ highlights that high CO_2 levels in classrooms impact children's errors in responding; therefore, among children who provide invalid and inconsistent responses to questionnaires, around 80% are tired or a little tired. It is shown that at concentrations over 1000 ppm, failures in decision making start to show and that at 2500 ppm failure in decision making is clear.³¹ Coley et al (2007) show that in classrooms where CO_2 levels are high, students are less attentive and cannot concentrate well on what the teacher is saying, which over time can have detrimental effects on their learning performance.³² CO_2 is seen as a harmless gas and is given little significance⁹⁶; however, as it contributes directly to the loss of concentration and increased tiredness,⁹⁸ it should be regarded as a very significant air pollutant.⁹⁶ By lowering CO_2 levels and improving IAQ, children would feel more comfortable and less tired,^{7,65,96} which can consequently increase their productivity and learning performance.^{31,99}

The importance of ensuring acceptable IAQ in classrooms is distinguished as a contributing factor to the learning performance of students.¹⁰⁰ Mechanisms that mediate the effects of thermal conditions and IAQ on performance are similar⁸⁶; therefore, it is expected to improve both collectively.

4 | CONCLUSION

This paper has focused on factors influencing children's perception of IAQ in primary school classrooms during non-heating and heating seasons. The study suggests that children's perception of IAQ depends on "at-the-time CO_2 level" which refers to the last 5 minutes of CO_2 measurement because children adapt to the classroom's IAQ after 5 minutes. Therefore, studying CO_2 levels within short intervals reflects children's perception of IAQ more reliably than looking at average CO_2 levels.

This study also highlights that indoor operative temperature and perception of the thermal environment (T_{op} and TSVs) impact children's perception of IAQ. High temperatures and children's poor perception of thermal environment reduce children's acceptance of IAQ, even when CO_2 levels are within acceptable limits. Low CO_2 levels fail to provide acceptable IAQ when children are thermally uncomfortable in classrooms. According to results of this study, children's perception of IAQ deteriorates significantly when CO_2 level goes above 1000 ppm and the operative temperature goes above the upper limit of thermal comfort band (above 23°C in this study). When $\text{CO}_2 < 1000$ ppm and $T_{\text{op}} < 23^\circ\text{C}$, only 10% of children have "Stuffy/Very stuffy" votes, while this amount triples when $\text{CO}_2 > 1000$ ppm and $T_{\text{op}} > 23^\circ\text{C}$. These findings urge school stakeholders and especially building management systems (BMS) to control CO_2 levels and indoor operative temperatures collectively to improve children's perception of IAQ. Standards and regulations should also consider both CO_2 levels and T_{op} to evaluate IAQ.

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CONFLICT OF INTEREST

The authors declare that no conflict of interest could be perceived as prejudicing the impartiality of the research reported.

AUTHOR CONTRIBUTIONS

Sepideh Sadat Korsavi: Conceptualization (lead); Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Visualization (lead); Writing-original draft (lead); Writing-review & editing (lead). **Azadeh Montazami:** Conceptualization (supporting); Funding acquisition (lead); Resources (lead); Supervision (lead); Visualization (equal); Writing-review & editing (equal). **Dejan Mumovic:** Visualization (supporting); Writing-review & editing (supporting).

NOMENCLATURE

Symbols

T_{op}	Operative Temperature (°C)
V	Air Speed (m/s)
CO_2	CO_2 level
RH	Relative Humidity (%)
P -value	Significance of correlation Coefficient
R^2	Coefficient of Determination

Abbreviations

Cor, Correlation; Sig., Significance of correlation Coefficient; No., Number; Vo, Volume; Orn, Orientation.

Parameters

IAQ	Indoor Air Quality
TSV(s)	Thermal Sensation Vote(s)
ASV(s)	Air Sensation Vote(s)
SD	Standard Deviation
PPD	Predicted Percentage Dissatisfied
NV	Naturally Ventilated
WA	Window Area
NW	Number of Windows
MHW	Minimum Height of Windowsill
ACRs	Air Change Rates
VRs	Ventilation Rates

PEER REVIEW

The peer review history for this article is available at <https://publons.com/publon/10.1111/ina.12740>.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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